

# A posteriori reading of Virtual Impactors impact probability

Germano D'Abramo

Istituto di Astrofisica Spaziale e Fisica Cosmica,  
Area di Ricerca CNR Tor Vergata, Roma, Italy  
E-mail: [dabramo@rm.iasf.cnr.it](mailto:dabramo@rm.iasf.cnr.it)

## Abstract

In this paper we define the *a posteriori* probability  $W$ . This quantity is introduced with the aim of suggesting a reliable interpretation of the actual threat posed by a newly discovered Near Earth Asteroid (NEA), for which impacting orbital solutions (now commonly known as Virtual Impactors or VIs) can not be excluded on the basis of the available astrometric observations. The probability  $W$  is strictly related to the so-called background impact probability (that extrapolated through a statistical analysis from close encounters of the known NEA population) and to the annual frequency with which the impact monitoring systems (currently NEODyS-CLOMON at University of Pisa and SENTRY at NASA-JPL) find VIs among newly discovered asteroids. Of  $W$  we also provide a conservative estimate, which turns out to be of nearly the same order of the background impact probability. This eventually says to us what we already know: the fact that nowadays monitoring systems frequently find VIs among newly discovered asteroids does not make NEAs more threatening than they have ever been.

## 1 Introduction

Soon after a new Near Earth Asteroid (NEA) is discovered, a preliminary orbit is computed using its positions in the sky over a suitable interval of time

(astrometric observations). Like every physical measurements, astrometric ones are affected by errors which make the orbit uncertain to some variable degree. Sophisticated mathematical and numerical tools are currently available to orbit computers which allow to propagate such measurement errors to the six orbital elements which identify the orbit of the asteroid. For this reason, the new NEA, soon after its discovery, is not represented by a single point in the 6-dimensional dynamical elements space; rather, it is represented by an uncertainty region, a 6-dimensional volume with diffused contours. Obviously, the volume of this uncertainty region changes (usually shrinks) when new more observations become available and the orbit refines.

Moreover, when the nominal orbit of the new NEA is geometrically close to the orbit of the Earth, and it shares some other peculiar orbital characteristics, it can happen that some orbital solutions which lead to a future collision of the asteroid with the Earth can not be excluded only on the basis of the available astrometric observations. Namely, orbital solutions which lead to a collision are inside the uncertainty region and they are fully compatible with the available astrometric observations and their errors.

What is substantially done in these cases by the researchers, with various sophisticated techniques whose description is well beyond the scope of this paper (see Milani *et al.*, 2000; 2003), is to sample the uncertainty region according to a suitable frequency distribution (closely related to what is currently known about error statistics) and then evaluate the relative probability that the “true” orbit of the asteroid is one among the collision ones. From now on we will refer to this probability with the symbol  $\mathcal{V}_i$ . The collision orbits are nowadays commonly called Virtual Impactors (or VIs; for an exhaustive review see Milani *et al.*, 2003).

Every time new more astrometric observations become available, the quality of the asteroid orbit improves and the estimated impact probability  $\mathcal{V}_i$  is re-computed. Its value is almost always such that  $\mathcal{V}_i \ll 1$  and during the phases of the orbital refinement it fluctuates, usually with a somewhat increasing trend<sup>1</sup> until it falls to zero, its most probable final value.

Starting from 1999, some press announcements were made regarding as many newly discovered NEAs which were found to have non zero collision chances in the near future (given the highly chaotic dynamics involved in

---

<sup>1</sup>The reason of such increasing behavior is rather technical and it is essentially connected to the fact that uncertainty region shrinks with new more observations.

the multiple planetary close encounters, which are at the basis of the impact calculations, impact analysis procedures can safely cover only time spans of the order of a century). The computations were carried out mainly by two research groups, that at the University of Pisa and that at NASA–JPL. One of the first and, maybe, most famous of such cases was that of asteroid 1999 AN<sub>10</sub> (for more informations, see for example Milani *et al.*, 1999; 2003 and <http://impact.arc.nasa.gov/news/1999/apr/21.html>; for a detailed historical account of these cases, see Chapman, 1999), being that of the asteroid 2002 NT<sub>7</sub> the most recent one (up to this date). These objects obviously rose the somewhat alarmed attention of the public opinion and of the whole astronomical community for a while. Then, after the asteroids orbits were refined thanks to new more astrometric observations and the impact possibilities ruled out, they have become again of purely academic interest.

Currently, the only two existing automatized VIs monitoring systems, CLOMON<sup>2</sup> at University of Pisa and SENTRY<sup>3</sup> at NASA–JPL, find tens of newly discovered NEAs with VIs orbital solutions every years, and some with not so small impact probability (for a preliminary statistics of VIs detections see Tab. 1, more later).

Given such past experience of public (and professional) reactions and given the current rate of VIs orbital solutions discovery, some questions rise to the author’s mind: how are VIs impact probabilities actually related to the real impact threat? How much threat should we reliably read in a VIs detection announcement? Equivalently, soon after the discovery of VIs orbital solutions of a new asteroid, what is the probability that  $\mathcal{V}_i$  approaches and eventually reaches the unity (within this paper we will use the compact notation “ $\mathcal{V}_i \rightarrow 1$ ”), after the right amount of new more astrometric observations has become available?

In this paper we would give a statistical, *a posteriori* reading of VIs impact probabilities (which actually are in their very nature “deterministic”, or, more properly, *a priori*) in order to provide an answer to such questions.

---

<sup>2</sup><http://newton.dm.unipi.it/neodys>

<sup>3</sup><http://neo.jpl.nasa.gov/risk/>

## 2 Statistical reading of $\mathcal{V}_i$

Soon after the discovery of VIs orbital solutions of a new asteroid, what is the probability of  $\mathcal{V}_i \rightarrow 1$ , after the right amount of new more astrometric observations has become available? It would seem quite obvious that this probability is simply  $\mathcal{V}_i$ , according to its definition. But we believe that this is not the case. This is essentially because  $\mathcal{V}_i$ , as we said before, fluctuates every time new more astrometric observations become available and the computations are redone: which particular value should we consider for our needs? The value obtained with the second batch of astrometric observations following the discovery observations? Or the third? Or just the value of  $\mathcal{V}_i$  calculated with the discovery observations? And, in latter case, if the discovery was made in another period of the year, the calculated value of  $\mathcal{V}_i$  would have been the same? Actually, what we are asking is: only knowing that a newly discovered NEAs exhibits some VIs orbital solutions, what is the probability that  $\mathcal{V}_i$  will be equal to 1 at the end of the whole orbital refinement process? We believe that only a statistical, *a posteriori* analysis can give an acceptable and verifiable answer.

Now, let us make the following thought experiment, only functional to the presentation of our point. Suppose that we are able to discover *all* asteroids with absolute magnitude less than or equal to  $H$  which pass close to the Earth. Moreover, we reasonably suppose that every discovered impacting asteroid will show some VIs, with low  $\mathcal{V}_i$  soon after the discovery and fluctuating with an increasing trend as soon as subsequent astrometric observations become available. In other words, we are putting ourselves in the somewhat idealized situation where *every* impacting asteroid brighter than  $H$  will surely be discovered and for it VIs monitoring systems will surely spot some VIs soon after its discovery.

Thus, we define the *a posteriori* probability of  $\mathcal{V}_i \rightarrow 1$ , which could be also interpreted as a kind of “weight” of the VIs impact probability calculation (more on this later), as:

$$W(\leq H) = \frac{n(\leq H)}{v(\leq H)} \Big|_T = \frac{\rho_i(\leq H)}{f_{\mathcal{V}_i}(\leq H)}, \quad (1)$$

where  $n(\leq H)$  is the number of impacts of asteroids with absolute magnitude less than or equal to  $H$  and  $v(\leq H)$  is the number of asteroids with same size found among all the newly discovered NEAs to exhibit VIs orbital solutions,

both counted in the period of  $T$  years. Note that, according to what we said at the beginning of this section, the number  $n(\leq H)$  is counted in the number  $v(\leq H)$ , since we have assumed that every impacting asteroid is identified soon after its discovery as having some VI orbital solutions.

Let us explain better the meaning of eq. (1). Within the hypotheses introduced above on the almost perfect NEAs discovery efficiency and VIs monitoring capabilities, we imagine to be able to wait for a very long period of years ( $T$ ) and count the number  $n(\leq H)$  of asteroid impacts and the number  $v(\leq H)$  of VIs orbital solutions detected among all the discovered NEAs below the characteristic absolute magnitude  $H$ , within that period of time. Hence the fraction of these two numbers gives the *a posteriori* probability that a newly discovered asteroid, for which the VIs monitoring systems have spotted some VIs orbital solutions, is just that which will fall on the Earth. In the third member of eq. (1) we rewrite  $W$  in terms of the background annual impact frequency  $\rho_i$ , namely that extrapolated through a statistical analysis from close encounters of the known NEA population (Morrison *et al.*, 2003), and the annual frequency  $f_{\mathcal{V}_i}$  of finding VIs among the newly discovered NEAs. A sketch of the average time between impacts ( $1/\rho_i$ ) is given in Fig. 1 as a function of the impactor’s diameter.

Above we said that  $W$  can be interpreted as a kind of “weight” of the VIs impact probability calculation. This is because the greater is  $f_{\mathcal{V}_i}$ , the lesser is the *a posteriori* probability of  $\mathcal{V}_i \rightarrow 1$ , no matter how is the initial numerical value of  $\mathcal{V}_i$ . Namely, the higher is the frequency with which we find VIs among newly discovered asteroids (with respect to the background frequency of impact,  $\rho_i$ ), the lesser is their *a posteriori* weight in expressing the threat of those particular newly discovered asteroids. This mechanism shares inevitable analogies with the well-known “crying wolf” experience, bad faith apart.

Moreover, we can see that  $W$  is not directly related to the specific numerical value of  $\mathcal{V}_i$ . Rather, it depends upon  $f_{\mathcal{V}_i}$ , namely the annual rate of VIs discovery, which, in turn, depends upon some observational characteristics. These are the annual number of NEA discoveries, the number of astrometric observations available at discovery, the magnitude of astrometric errors and the conventions in their statistical treatment and the observational geometry and orbital characteristics of the newly discovered asteroid. But, we guess, it is not easy to give an exact estimate of its value at the moment. A greater sample of VIs detections is necessary in order to better estimate  $f_{\mathcal{V}_i}$  and thus

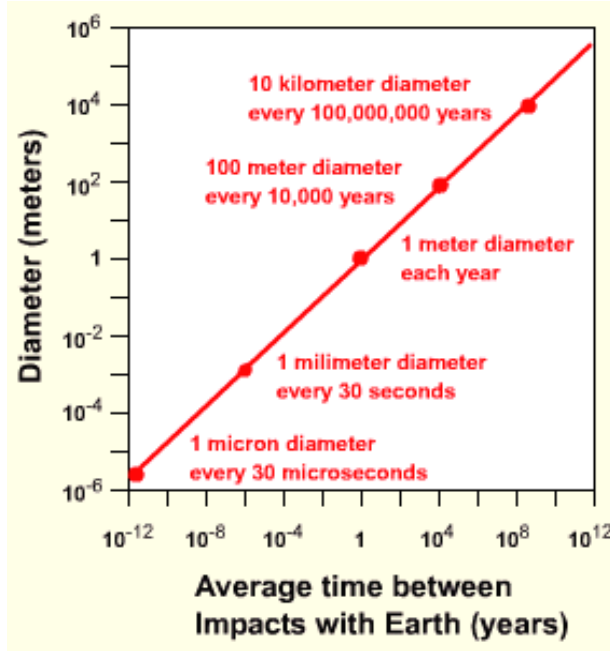


Figure 1: An approximation of the average time between asteroidal impacts with the Earth (the reciprocal of the background annual impact frequency  $\rho_i$ ) as a function of the impactor's diameter. We choose to use diameters ( $D$ ) rather than absolute magnitudes ( $H$ ) since diameters are a more direct physical quantity. The mathematical relation between  $D$  and  $H$  is:  $\log_{10} D \simeq \log_{10} 1329 - \frac{H}{5} - \frac{1}{2} \log_{10} p_V$ , where  $p_V$  is the albedo of the asteroid and it is usually assumed to be equal to 0.15 (Chesley *et al.*, 2002).

the probability  $W$ .

Anyway, having an idea of the total number of VIs detections found at every size between calendar years 2000 and 2001 (for this, a sufficient but not complete archive of VIs detections could be found in the web pages of the Observing Campaigns of the Spaceguard Central Node at <http://spaceguard.rm.iasf.cnr.it>), a conservative estimate of  $W$  cannot be too much different from that we get with  $f_{V_i}$  of the order of the unity. From Tab. 1 we see that the numerical value of  $f_{V_i}$  varies between  $\sim 1$  and  $\sim 10$ , in the reported range of absolute magnitudes  $H$ . For the sake of simplicity, in this paper we choose to adopt  $f_{V_i} \sim 1$  for all  $H$ , being confident of committing a justifiable

approximation, surely comparable with the uncertainty with which  $\rho_i$  is currently known (at least within some ranges of absolute magnitude). In that way, we simply have  $W \sim \rho_i$ .

Note that relaxing the optimistic assumptions on the almost perfect NEAs discovery efficiency and VIs monitoring capabilities makes  $f_{\mathcal{V}_i}$ , as approximated with the aid of Tab. 1, even an underestimate, and consequently it makes  $W \sim \rho_i$  an overestimate.

Therefore, the probability of  $\mathcal{V}_i \rightarrow 1$  is nearly of the order of the background impact probability, no matter how is  $\mathcal{V}_i$ 's specific, initial (fluctuating) numerical value.

This result should not be a surprise since it simply re-states what we already know: the actual impact threat of the unknown NEA population on the Earth is always the same estimated through the close encounters statistics of known population. The fact that in the last few years many VIs orbital solutions have been detected among newly discovered NEAs obviously does not make NEAs more threatening than they have ever been.

As a matter of fact, the annual rate of VIs detections, if compared with the background impact probability, suggests an order of magnitude of the weight VIs detections have in expressing the real threat of a newly discovered NEA with  $\mathcal{V}_i \neq 0$ .

### 3 Conclusions

From the introduction and the discussion of the *a posteriori* probability  $W$  done in this paper it follows that, rigorously speaking, the VIs impact probability  $\mathcal{V}_i$  does not give the real expression of the actual impact threat posed by a newly discovered NEA exhibiting VIs orbital solutions. This is properly done by  $W$ , which is strictly related to the so-called background impact probability  $\rho_i$  (that extrapolated through a statistical analysis from close encounters of the known NEA population) and to the annual frequency with which the impact monitoring systems (currently NEODyS-CLOMON at University of Pisa and SENTRY at NASA-JPL) find VIs among newly discovered asteroids. Of  $W$  we also provide a conservative estimate, which turns out to be of nearly the same order of  $\rho_i$ .

All this might seem a bit paradoxical, given the definition of  $\mathcal{V}_i$ . Yet, a closer look to the definition of  $W$  shows that our conclusions are straightfor-

Table 1: Annual frequency of VIs detections below absolute magnitude  $H$ , estimated using the Spaceguard Central Node archive of VIs observing campaigns organized in the calendar years 2000 and 2001. During that period of time there were no VIs detections below  $H = 16$ . In the reported range of  $H$ , the numerical value of  $f_{V_i}$  varies between  $\sim 1$  and  $\sim 10$ .

$H$	$f_{V_i}(\leq H)$ $\text{yr}^{-1}$
29	14.5
28	14.0
27	14.0
26	13.5
25	13.0
24	9.5
23	9.5
22	8.5
21	7.5
20	7.0
19	5.5
18	3.5
17	1.5
16	$\sim 1$

ward and even obvious.

## References

Chapman, C.R., 1999. The asteroid/comet impact hazard. Case Study for *Workshop on Prediction in the Earth Sciences: Use and Misuse in Policy Making*, July 10-12 1997 - Natl. Center for Atmospheric Research, Boulder, CO and September 10-12 1998, Estes Park, CO. Available on-line at: <http://www.boulder.swri.edu/clark/ncar799.html>



Chesley, R.S., Chodas, P.W., Milani, A., Valsecchi, G.B., Yeomans, D.K., 2002. Quantifying the risk posed by potential Earth impacts. *Icarus*, in press.

Milani, A., Chesley, S.R., Valsecchi, G.B. 1999. Close approaches of asteroid 1999 AN<sub>10</sub>: resonant and non-resonant returns. *Astronomy & Astrophysics* 346:L65-L68.

Milani, A., Chesley, S.R., Valsecchi, G.B. 2000. Asteroid close encounters with Earth: Risk assessment. *Planetary & Space Science* 48: 945-954.

Milani, A., Chesley, S.R., Chodas, P.W., Valsecchi, G.B. Asteroid close approaches and impact opportunities. Chapter for *Asteroids III* book edited by William Bottke, Alberto Cellino, Paolo Paolicchi, and Richard P. Binzel. University of Arizona Press, Tucson (2003).

Morrison, D., Harris, A.W., Sommer, G., Chapman, C.R., Carusi, A. Dealing with the Impact Hazard. Chapter for *Asteroids III* book edited by William Bottke, Alberto Cellino, Paolo Paolicchi, and Richard P. Binzel. University of Arizona Press, Tucson (2003).